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LONGITUDINAL AERODYNAMIC CHARACTERISTICS IN GROUND EFFECT OF A LARGE-SCALE, V/STOL MODEL WITH FOUR TILTING DUCTED FANS ARRANGED IN A DUAL TANDEM CONFIGURATION

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LONGITUDINAL AERODYNAMIC CHARACTERISTICS IN GROUND EFFECT OF A LARGE-SCALE, V/STOL MODEL WITH FOUR TILTING DUCTED FANS ARRANGED IN A DUAL TANDEM CONFIGURATION

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SUMMARY

Measurements were made at three ground heights for duct incidence settings required for airspeeds ranging from hover to cruise. Forward speed, fuselage angle of attack, and duct exit vane deflection were varied. The model had favorable ground effects on lift at hover. For test conditions representing STOL operation, the ground effects on lift varied from favorable to adverse to no effect for duct incidences of 70°, 50°, and less than 30°, respectively. Longitudinal stability varied with approaching ground such that reverse control inputs would be required for trim.

INTRODUCTION

There is little information on the basic aerodynamic characteristics of full-scale ducted fans. Reference 1 reported results of a study made in the 40- by 80-foot wind tunnel of the general aerodynamic characteristics out of ground effect of a large scale, complete model of a vertical and short takeoff and landing (V/STOL) aircraft having four tilting ducted fans arranged in tandem pairs. The present paper reports on tests that were an extension of that program and were made to determine the longitudinal aerodynamic characteristics of the same model in proximity to the ground.

Data were recorded at three ground heights at forward speeds ranging from 0 to about 110 knots. Fuselage angle of attack and duct incidence were varied. The duct incidences tested ranged from 90° on the four ducts (hover duct configuration) to 5° on the front ducts and 0° on the rear ducts (cruise duct configuration). Duct exit vane deflection was varied to study pitch control in proximity to the ground.

NOTATION

b   span of wing, ft

c   reference length, wing chord, ft

C_D drag coefficient, $\frac{D}{qS}$

C_L lift coefficient, $\frac{L}{qS}$

C_m pitching-moment coefficient, $\frac{M}{qSc}$

C_P power coefficient, $\frac{550\ HP}{\rho n^3 d^5}$

d fan diameter, ft

D drag, lb, or duct exit diameter, ft

h vertical distance from front duct exit to ground plane with front ducts rotated 90° (fig. 2(b)), ft

HP horsepower

J fan advance ratio, $\frac{V}{nd}$

L lift, lb

M pitching moment, ft-lb

N fan rotational speed, rpm

n fan rotational speed adjusted to standard sea-level temperature, $\frac{N}{60\sqrt{\theta}}$, rps

q free-stream dynamic pressure, lb/sq ft

S reference area, area of wing, sq ft

T thrust along fan axis, lb

T_c thrust coefficient with forward speed, $\frac{T}{qS}$

V free-stream velocity adjusted to sea level, standard conditions, fps or knots

α fuselage angle of attack, deg

δ_D duct incidence relative to fuselage, deg

δ_e fore-aft duct exit vane deflection relative to fan thrust axis, deg

θ relative temperature ratio, (ambient temperature)$^{\circ}$F + 460°/520°

ρ density, lb sec^2/ft^4

Subscripts

a aft

f forward

v vertical hover reference; $\frac{h}{D} = 3$, $\delta_D = 90^{\circ}$

Examples of Duct Incidence and Exit Vane Deflection Notation

$\delta_D = 50^{\circ}$	all four ducts at 50° incidence
$\delta_{D_f}/\delta_{D_a} = 5^{\circ}/0^{\circ}$	cruise duct configuration; 5° fore-aft differential duct incidence; forward ducts at 5° and aft ducts at 0°
$\delta_{e_f}/\delta_{e_a} = -20^{\circ}/20^{\circ}$	±20° fore-aft differential duct exit vane deflection (total of 40° deflection); positive total deflection when vane trailing edges are up on the forward vanes and down on the rear vanes

MODEL DESCRIPTION

The model used for these tests is the same model described in reference 1 except that the horizontal model support tube was shortened to reduce any effects of front duct slipstream impingement on the support tube. Photographs of the model installed on the variable height strut system in the test section of the Ames 40- by 80-Foot Wind Tunnel are shown in figure 1. Figure 2(a) and tables I and II (repeated from ref. 1) show model geometry, dimensional data, and shroud and centerbody coordinates, respectively. Ground height is defined in figure 2(b). Blade angle remained at 23° measured at the tip.

TESTS

Longitudinal force and moment data were obtained at three ground heights at forward speeds from 0 to about 110 knots. Forward speeds were generally chosen for about the same advance ratio and selected duct incidence used in the tests of reference 1 where advance ratio was established for conditions of about zero drag at 0° angle of attack. The general method of testing was to vary fuselage attitude at a selected ground height while duct incidence, forward speed, and fan speed remained fixed. Angle of attack was varied from -6° to +22° at the maximum ground height (h/D = 3). This angle-of-attack range decreased as ground height decreased. Duct incidences tested ranged from 90° on the four ducts (hover duct configuration) to 5° on the front ducts and 0°

on the rear ducts (cruise duct configuration). Pitch control was measured by varying fore-aft duct exit vane deflection which ranged from 0° to 40° of total deflection. Fan speeds were varied from about 2200 rpm to about 3000 rpm.

CORRECTIONS

No corrections were applied to the force and moment data to compensate for wind-tunnel wall interference effects as the magnitude of such corrections was not known. The force and moment data have been corrected for free-stream effects on the variable height struts and for 2° of flow inclination caused by the presence of the ground plane. A drag correction of 0.6 lb/lb/sq ft of dynamic pressure was estimated and applied to the drag and pitching-moment data to compensate for free-stream effects on the exposed horizontal model support tube.

RESULTS

Figure 3, repeated from reference 1 for convenient reference, shows isolated ducted fan thrust as a function of advance ratio for duct incidences from 0° to 80°.

The results of this investigation are presented in figures 4 through 9. The variations of model characteristics with ground height at hover and near hover duct incidences are shown in figures 4 and 5 for zero and low forward speeds, respectively. The longitudinal characteristics of figure 4 were made dimensionless by dividing the absolute forces and moments by the measured model static lift at $h/D = 3$ and 90° duct incidence. Figures 6 and 8 present basic model longitudinal aerodynamic characteristics at three ground heights at duct incidence settings for transition and cruise flight. Power variation in terms of power coefficient for the results of figure 6 is shown in figure 7. The results of figure 6 are with duct exit vanes undeflected and those of figure 8 show pitch control available with 40° of total duct exit vane deflection. Figure 9 presents longitudinal pitch control effectiveness in proximity to the ground.

DISCUSSION

Hover Ground Effect

Lift.- The model had an increase in lift and then a slight decrease in lift at constant rpm as ground was approached (fig. 4(a)). The results of figure 4(b) show a power reversal resulting in a reduction of power at constant rpm at ground heights of 1 and 2 duct diameters, with the largest reduction occurring at $h/D = 2$. Also included in figure 4(b) is an estimate of the power required with ground height change at constant lift. The power required at constant lift was reduced by about 9 percent at $h/D = 2$ from that required at $h/D = 3$. The previously noted power reversal was still evident.

Longitudinal control.- Longitudinal control for maneuvering and trim at hover would be obtained by differential fore-aft thrust or thrust vectoring. Pitching-moment variation with ground height changes shown in figure 4(a) indicates some control reversal would be required for trim at hover as ground was approached. These results at other than hover duct incidence and at zero forward speed may become significant during initial accelerations from hover to transition flight where, for the range of duct incidences tested, the largest trim requirement occurs at $\delta_D = 70^\circ$ and $h/D = 2$. At these conditions approximately ±5 percent of the reference hover thrust (vertical lift at $\delta_D = 90^\circ$ and $h/D = 3$) would be required for trim.

STOL

The results of figures 5(a) and 5(b) show model longitudinal aerodynamic characteristics at three ground heights at the low forward speeds associated with high duct incidences. These results are presented for a range of duct incidences to show the effects of ground proximity during decelerations in transition flight.

Lift.- Decreasing ground height at forward speed resulted in either adverse or favorable ground effects on lift at duct incidences of 70° and 50°, respectively (figs. 6(a), 6(b), and 6(c)). However, lift was unaffected by changes in ground height at duct incidences of 30° and less (figs. 6(d) and 6(e)). At these lower duct incidences, entrainment and interference effects with the ground plane would be least. As shown in figure 7, power was not affected by ground height changes.

Longitudinal stability.- The results of figure 6 show nearly neutral static stability except at high angles of attack at all ground heights tested. These results are similar to those out of ground effect reported in reference 1. At $\alpha = 0^\circ$, reducing ground height from 3 to 2 duct diameters caused a negative shift in pitching moment at all duct incidences. At duct incidences of 70° or 30°, and at cruise setting ($\delta_{D_f}/\delta_{D_a} = 5^\circ/0^\circ$) the moment shift was positive as ground height was reduced from 2 to 1 duct diameter. Trimming this ΔC_m shift at 30° duct incidence would require a total of about 7° of duct exit vane deflection, or approximately 17 percent of the total longitudinal control available from the exit vanes (fig. 9(b)). At 70° duct incidence, there was a lift loss with reduction in ground height (figs. 6(a) and 6(b)), thus the lift loss and moment reversal were probably due to recirculation effects. However, at the lower duct incidences (30° and cruise setting) lift was not significantly affected by ground proximity (figs. 6(d) and 6(e)), thus the moment changes reflect a redistribution of loading caused by interaction of the model, duct slipstreams, and ground plane.

Longitudinal control.- The performance of differentially deflected fore-aft duct exit vanes was studied for longitudinal trim and control at cruise and low duct incidences. As in reference 1, a total duct exit vane deflection of 40° ($\delta_{e_f}/\delta_{e_a}$ = -20°/20°) was assumed to be a limit of linear response. At all ground heights investigated this amount of control was inadequate for trim at 50° duct incidence (figs. 8(a) and 9(a)) but was sufficient for trim at duct incidences of 30° and less (figs. 8(b), 8(c), 9(b), and 9(c)). At duct incidences greater than 50°, some additional control such as differential fore-aft thrust would be required for trim. These results are similar to those for out of ground effect reported in reference 1 where the same amount of control became inadequate for trim beyond about 40° duct incidence but the duct exit vanes provided effective pitch control up to 60° duct incidence.

Pitch control effectiveness was approximately linear through 40° of total duct exit vane deflection (figs. 9(a), 9(b), and 9(c)). These results show the reversal of pitch as ground is approached and as discussed for the results of figure 6 at duct incidences of 30° and less with the maximum pitch unbalance occurring at $h/D = 2$. At these duct incidences, a reversal of control would be required for trim at one and two duct diameters from the ground.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Aug. 1, 1967
721-01-00-10-00-21

REFERENCE

1. Giulianetti, Demo J.; Biggers, James C.; and Maki, Ralph L.: Longitudinal and Lateral-Directional Aerodynamic Characteristics of a Large-Scale, V/STOL Model With Four Tilting Ducted Fans Arranged in a Dual Tandem Configuration. NASA TN D-3490, 1966.

TABLE I.- MODEL DIMENSIONAL DATA

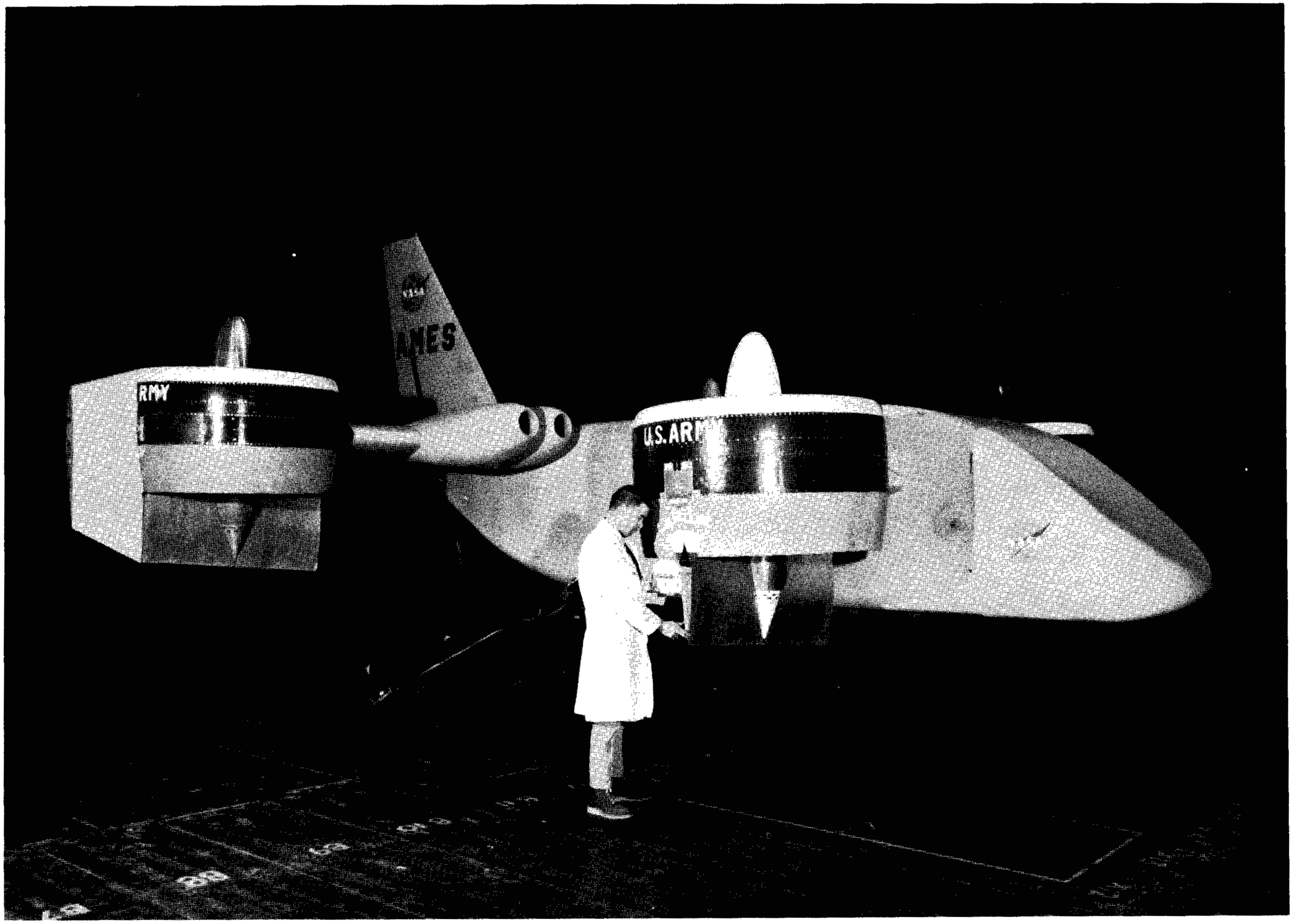
Wing	
Area, sq ft	74.30
Chord, ft	5.62
Span, ft	13.63
Aspect ratio	2.5
Taper ratio	1.0
Airfoil section:	
Maximum thickness ratio, percent chord	16.8
Position of maximum thickness, percent chord	33.6
Wing tips	
Area for one tip, sq ft	5.53
Aspect ratio	0.4
Taper ratio	0.7
Airfoil section	NACA 64A415
Ducts	
Inside diameter, ft	4.00
Outside diameter, ft	4.87
Exit diameter, ft	4.52
Chord, ft	2.75
Diffuser angle, deg	11
Duct exit vanes	
Area for one vane, sq ft	10.3
Aspect ratio	2.0
Taper ratio	0.8
Airfoil section	NACA 0012-64
Fan	
Fan diameter, ft	4.00
Number of blades	8
Blade angle at tip, deg	23

TABLE II.- SHROUD AND CENTERBODY COORDINATES

Shroud coordinates tabulated in percent of shroud chord (33.00 in.)		
Chordwise length	Outside radius	Inside radius
0	81.5	81.5
.5	83.4	79.6
.75	83.8	79.0
1.25	84.4	78.4
2.5	85.4	77.2
5.0	86.4	75.8
7.5	87.1	74.9
10.0	87.6	74.2
15.0	88.2	73.3
20.0	88.6	72.9
25.0		72.7
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		73.2
60.0		74.1
65.0	88.0	75.1
70.0	87.4	76.1
75.0	86.8	77.1
80.0	85.9	78.1
85.0	85.2	79.1
90.0	84.3	80.1
95.0	83.3	81.1
100.0	82.2	82.0

Centerbody coordinates tabulated in percent of centerbody length (71.5 in.)	
Length	Radius
0	0
.5	2.07
1.25	3.20
2.50	4.46
5.0	6.17
7.5	7.40
10.0	8.31
15.0	9.68
20.0	10.54
25.0	11.01
25.875[1]	11.06
30.0	11.19
32.57[2]	
40.0	
50.0	
60.0	
70.0	10.49
72.05[3]	10.14
80.0	7.97
83.20	6.77
90.0	4.03
95.0	2.01
100.0	0

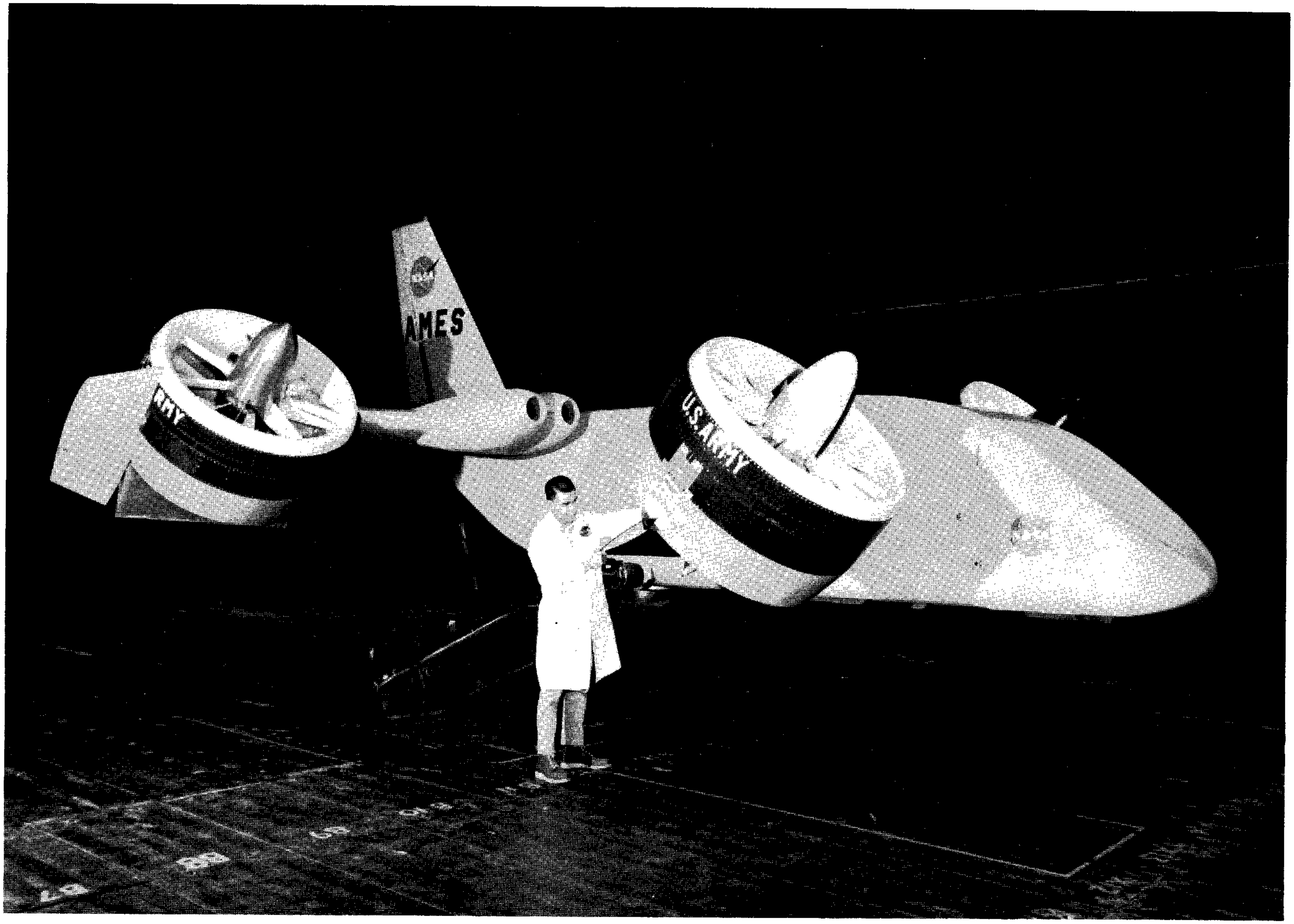
[1]Shroud leading-edge position
[2]Inlet guide vane c/4 line position
[3]Shroud trailing-edge position



A-34111

(a) Hover duct configuration; $\delta_D = 90^\circ$, $\delta_{e_f}/\delta_{e_a} = 0^\circ/0^\circ$.

Figure 1.- Model mounted in test section of Ames 40- by 80-Foot Wind Tunnel.



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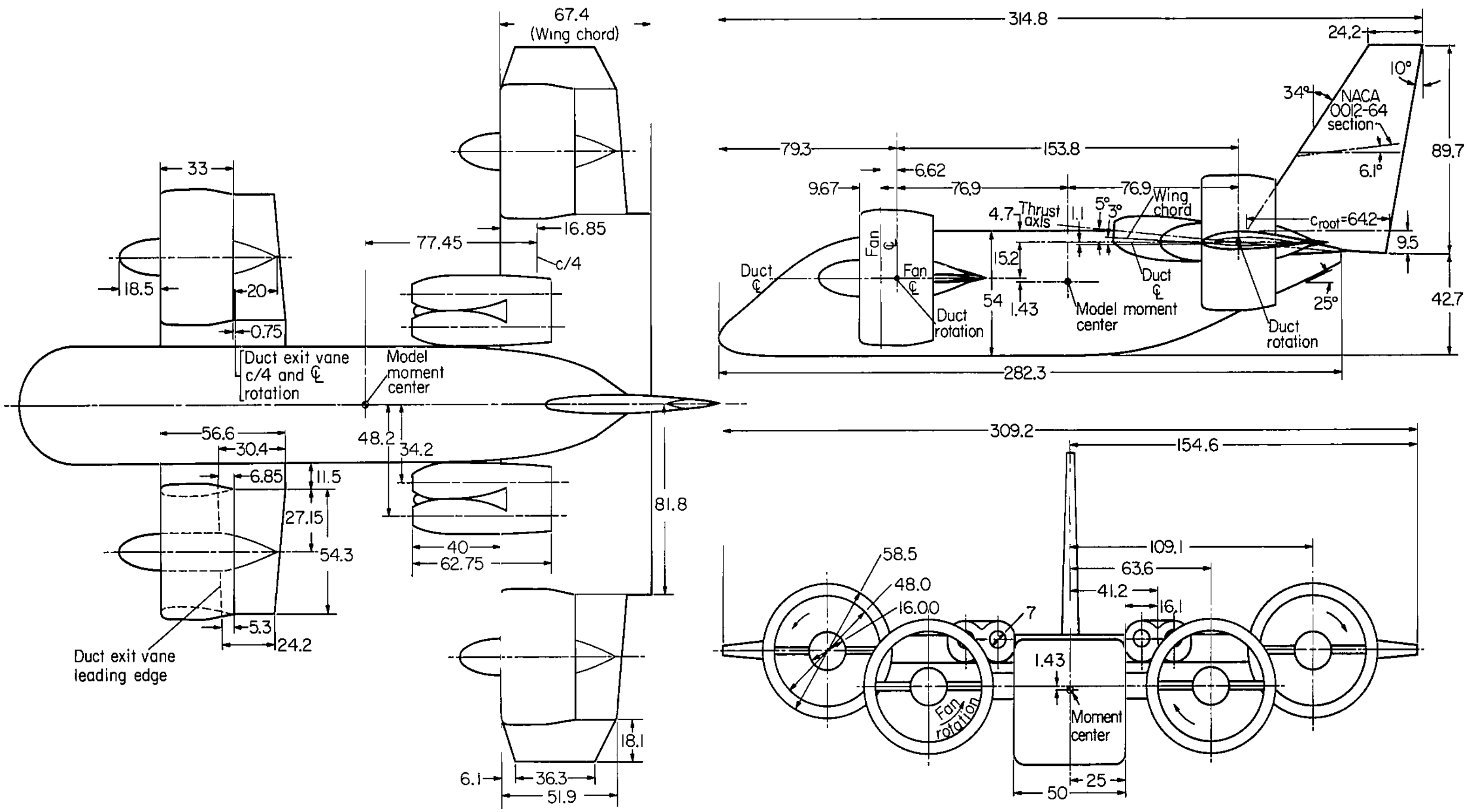
(b) $\delta_D = 45^\circ$, $\delta_{e_f}/\delta_{e_a} = -20^\circ/20^\circ$

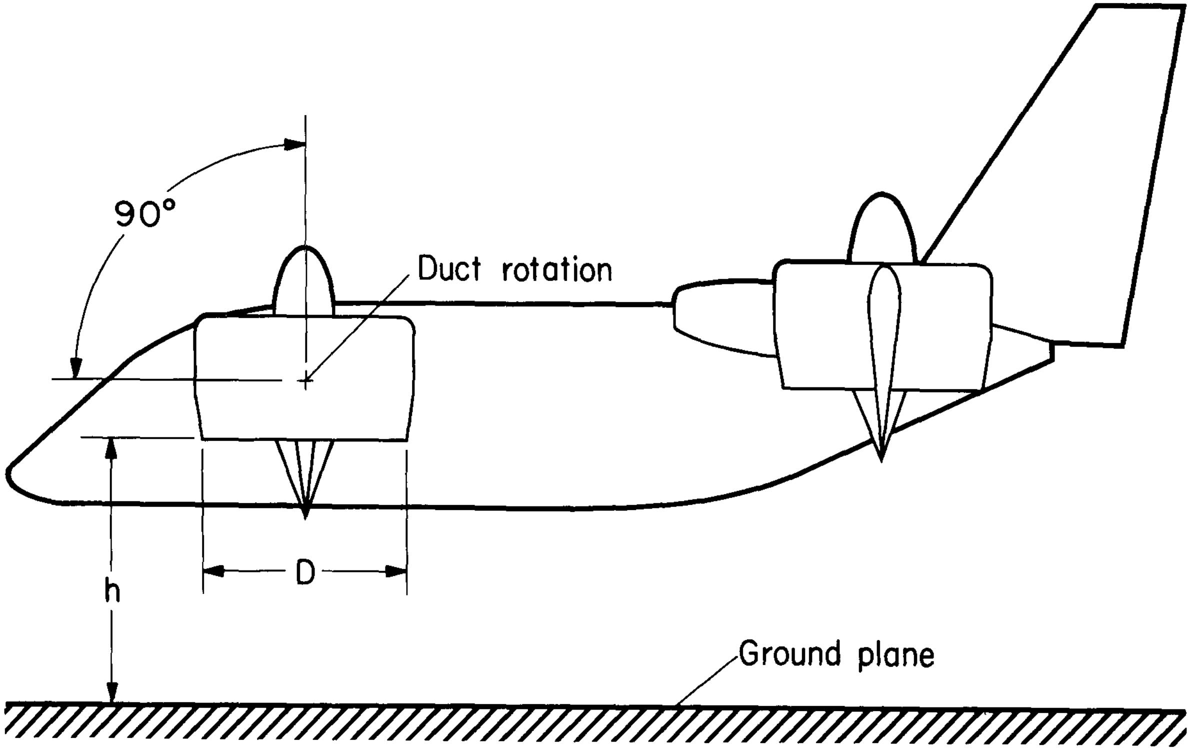
Figure 1.- Concluded.



All dimensions in inches

(a) Geometric characteristics of the model.

Figure 2.- Model dimensions and geometry.



(b) Ground height definition.

Figure 2.- Concluded.

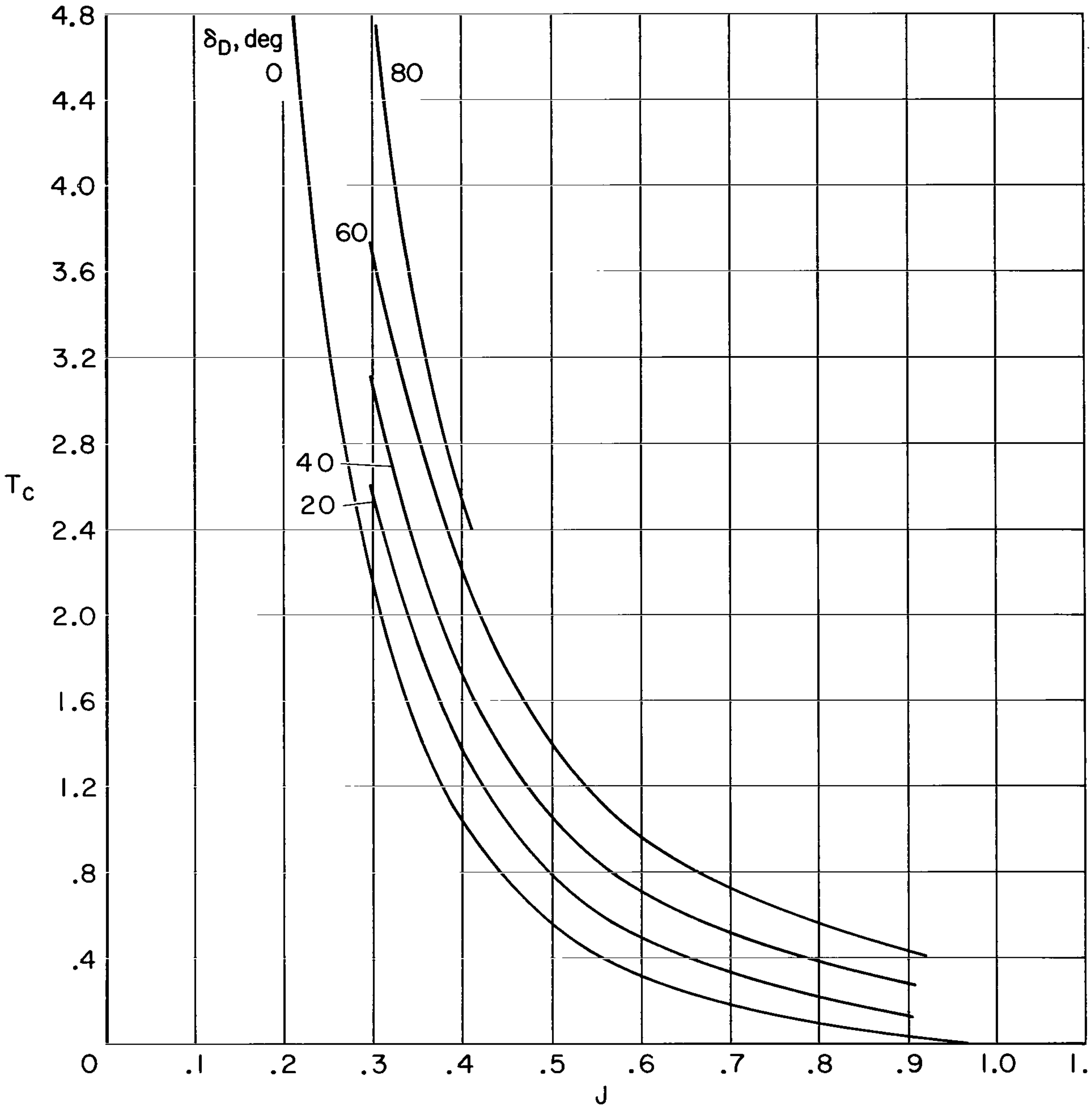
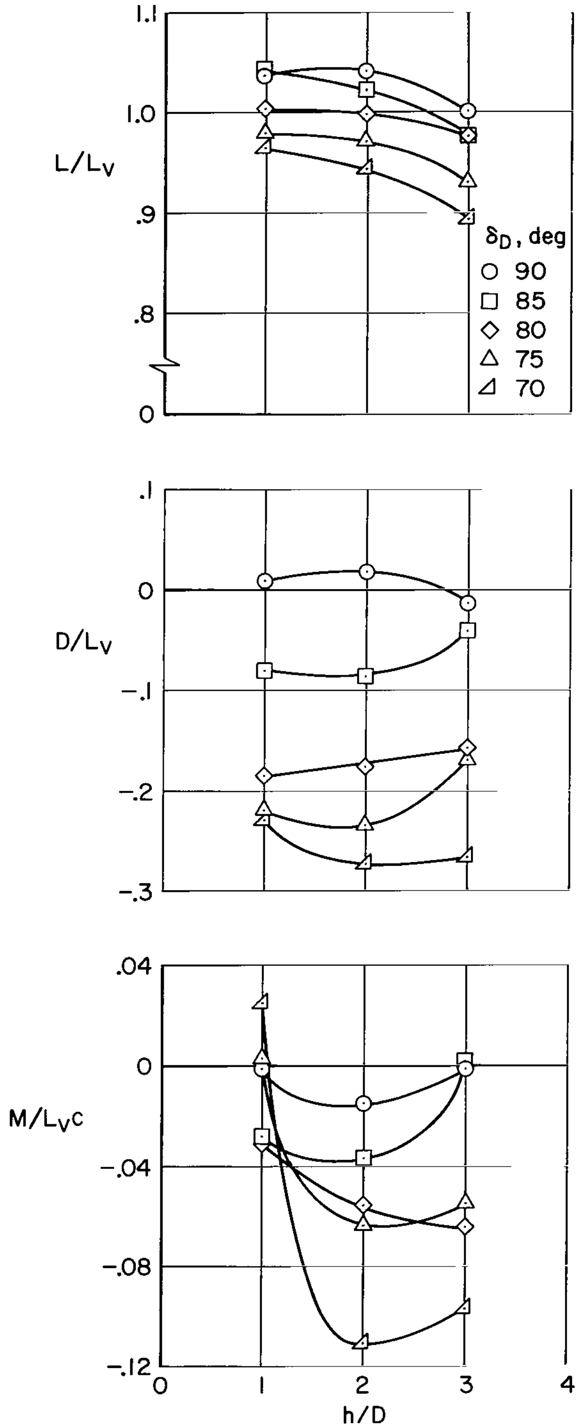
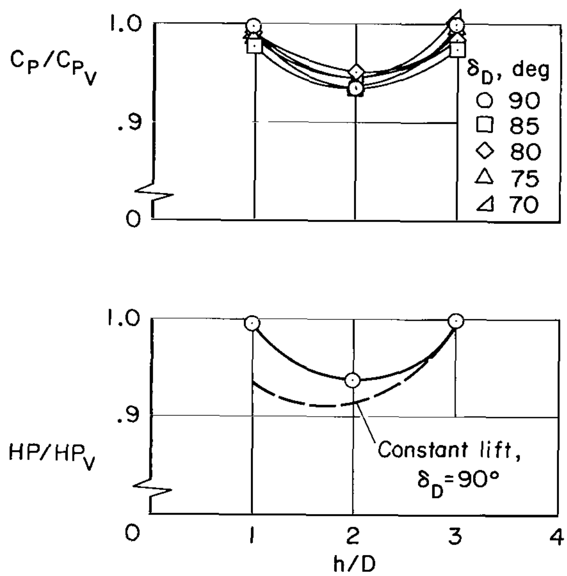


Figure 3.- Thrust coefficient as a function of advance ratio for the isolated ducted fan; blade angle = 23°.



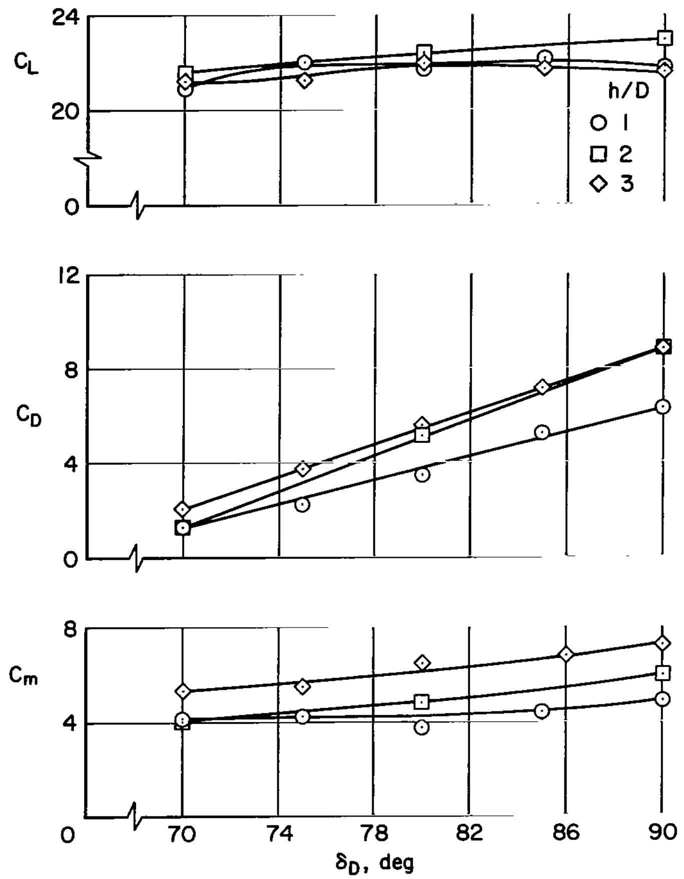
(a) Longitudinal aerodynamic characteristics.

Figure 4.- Performance at hover and zero forward speed; $\alpha = 0^{\circ}$, N = 3020 rpm, $\delta_{e_f}/\delta_{e_a} = 0^{\circ}/0^{\circ}$.



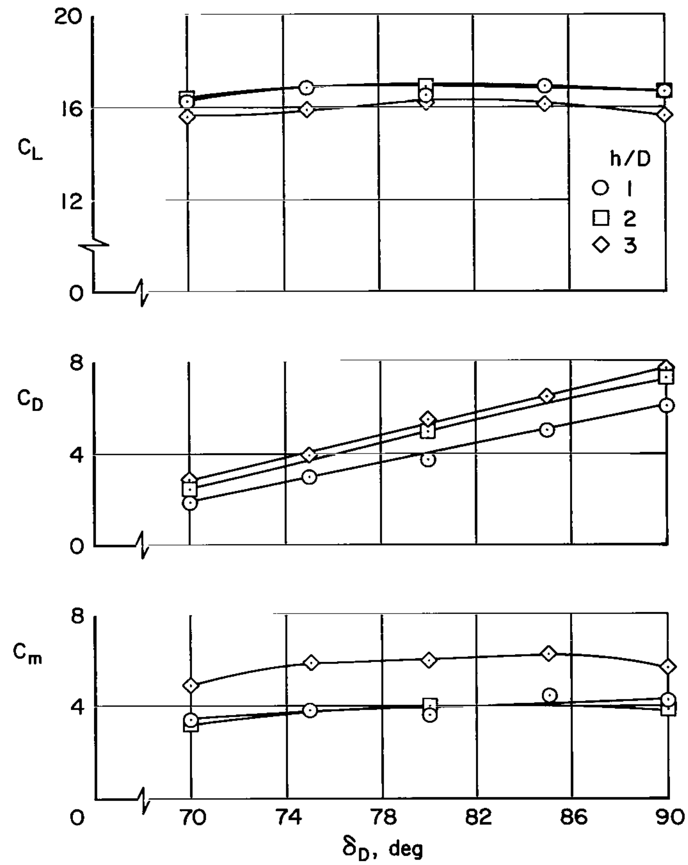
(b) Power characteristics.

Figure 4.- Concluded.



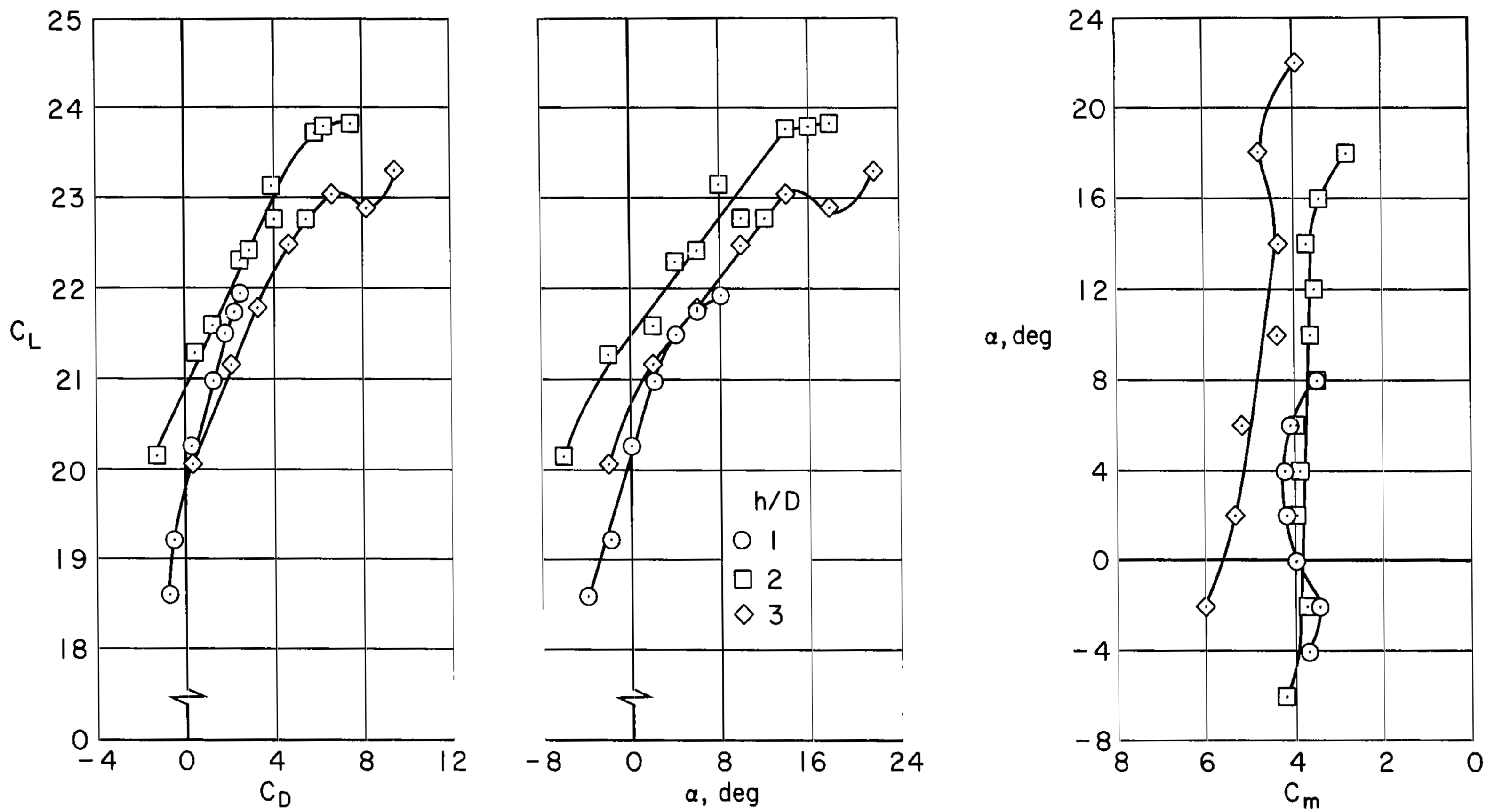
(a) V = 30 knots, J = 0.25

Figure 5.- Effect of ground height changes on the longitudinal aerodynamic characteristics of the model at hover and near hover duct incidences; $\alpha = 0^{\circ}$, $\delta_{e_f}/\delta_{e_a} = 0^{\circ}/0^{\circ}$.



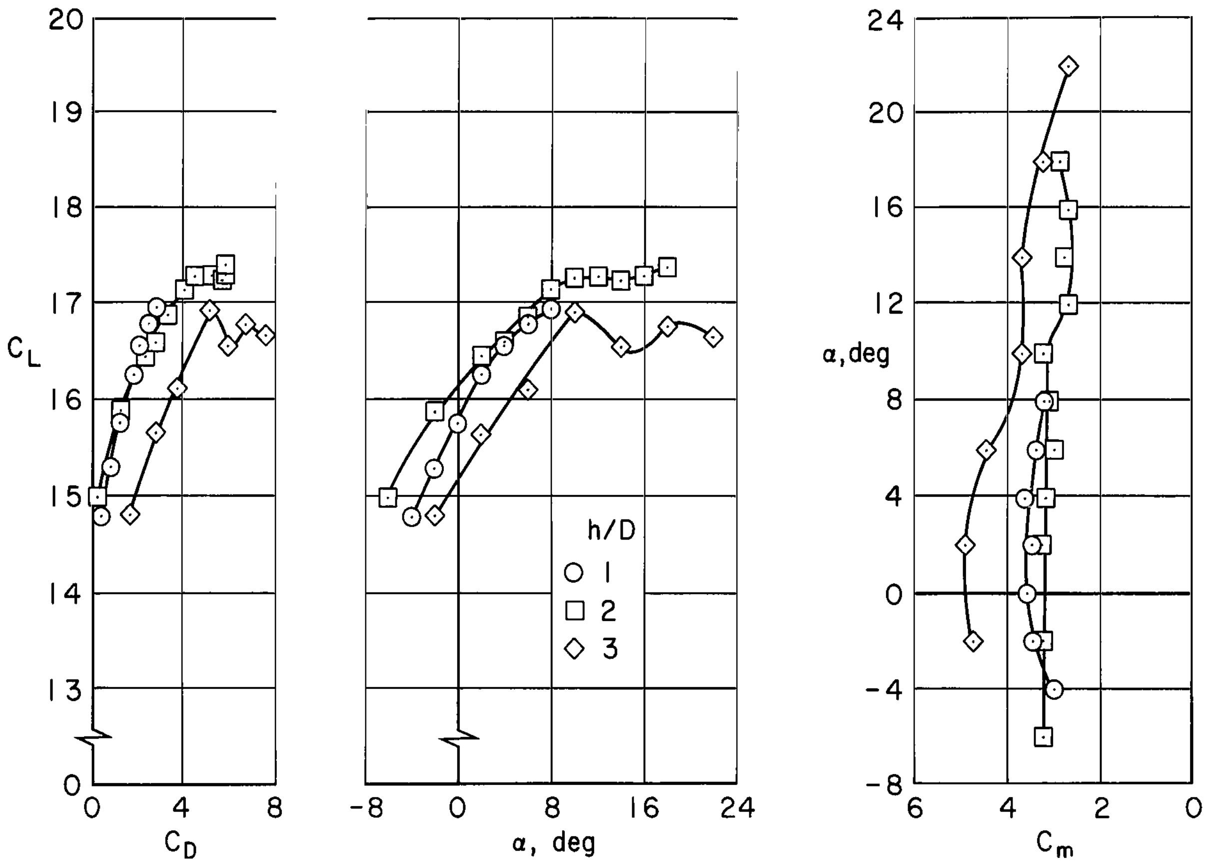
(b) V = 35 knots, J = 0.30

Figure 5.- Concluded.



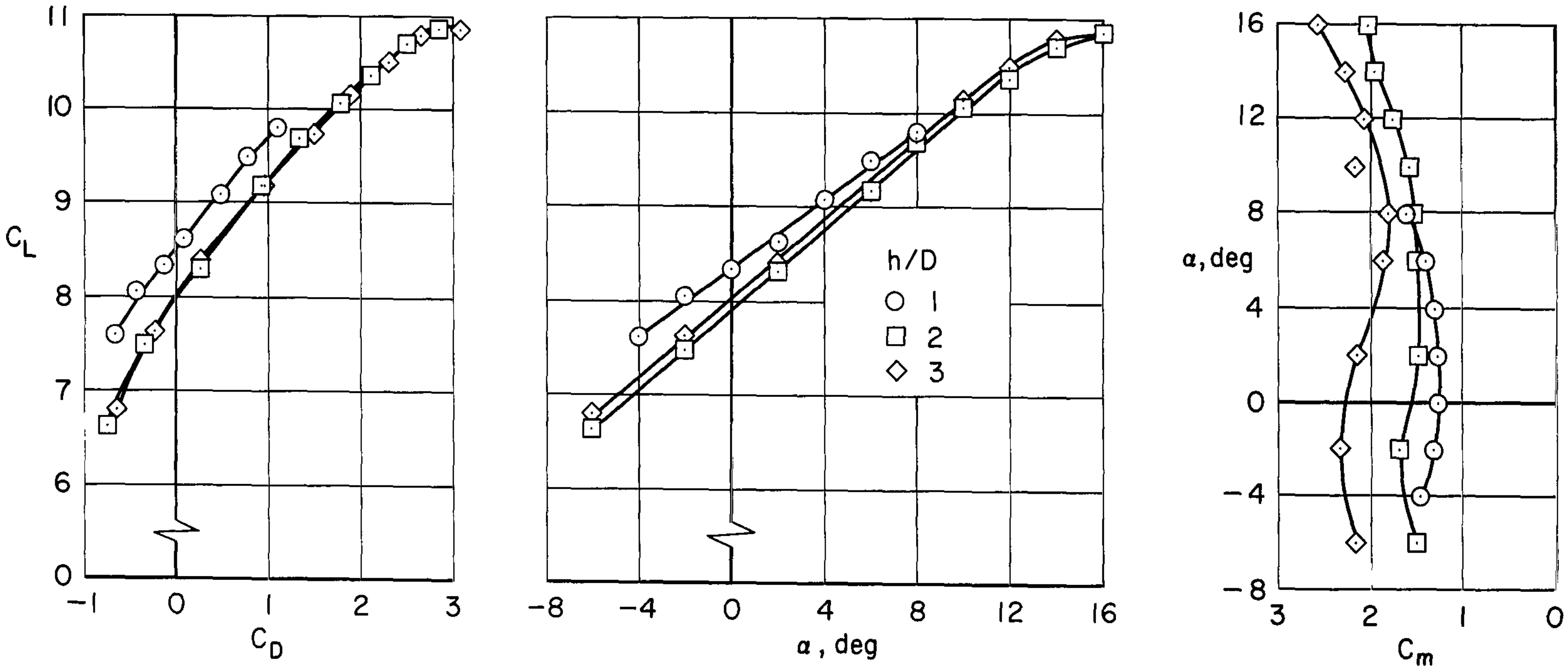
(a) $\delta_D = 70^\circ$, V = 30 knots, J = 0.25

Figure 6.- Longitudinal aerodynamic characteristics of the model at three ground heights; $\delta_{e_f}/\delta_{e_a} = 0^\circ/0^\circ$.



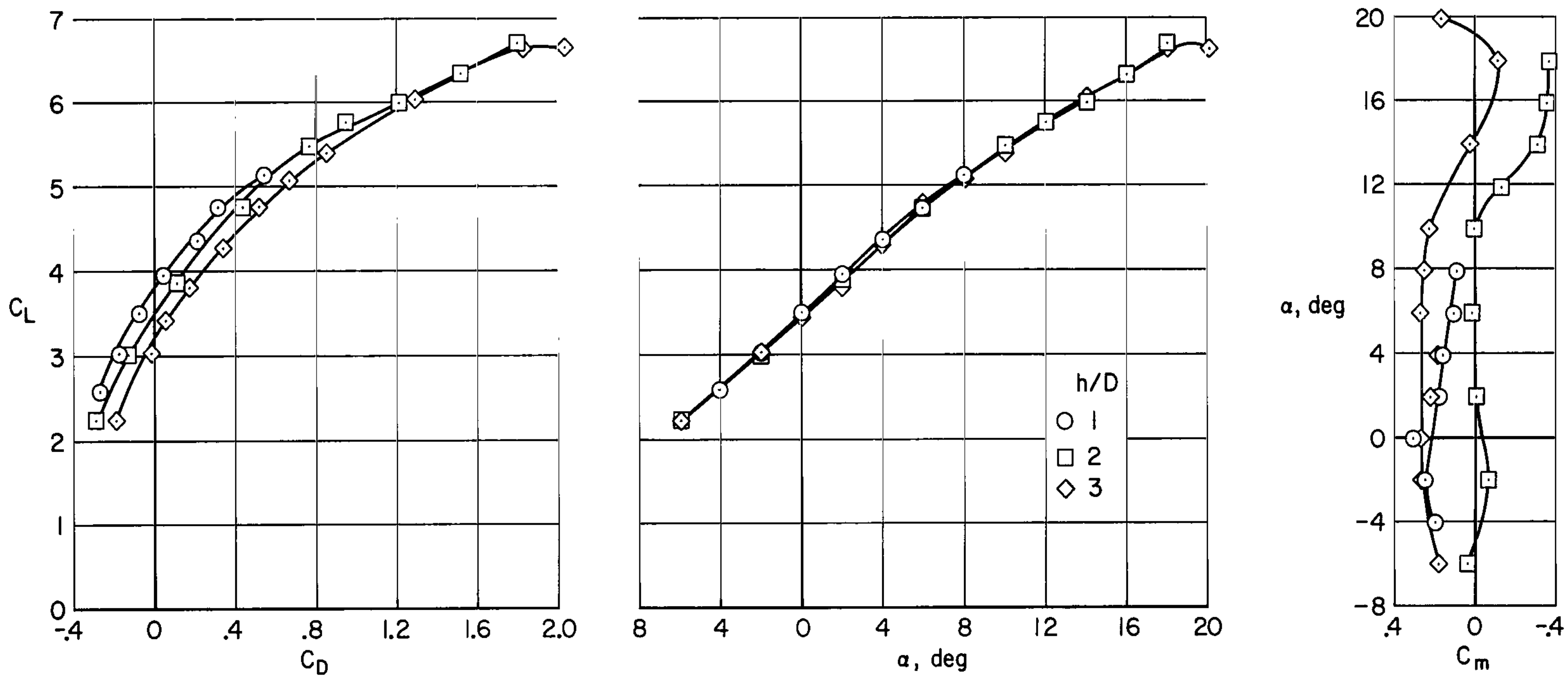
(b) $\delta_D = 70^\circ$, V = 35 knots, J = 0.30

Figure 6.- Continued.



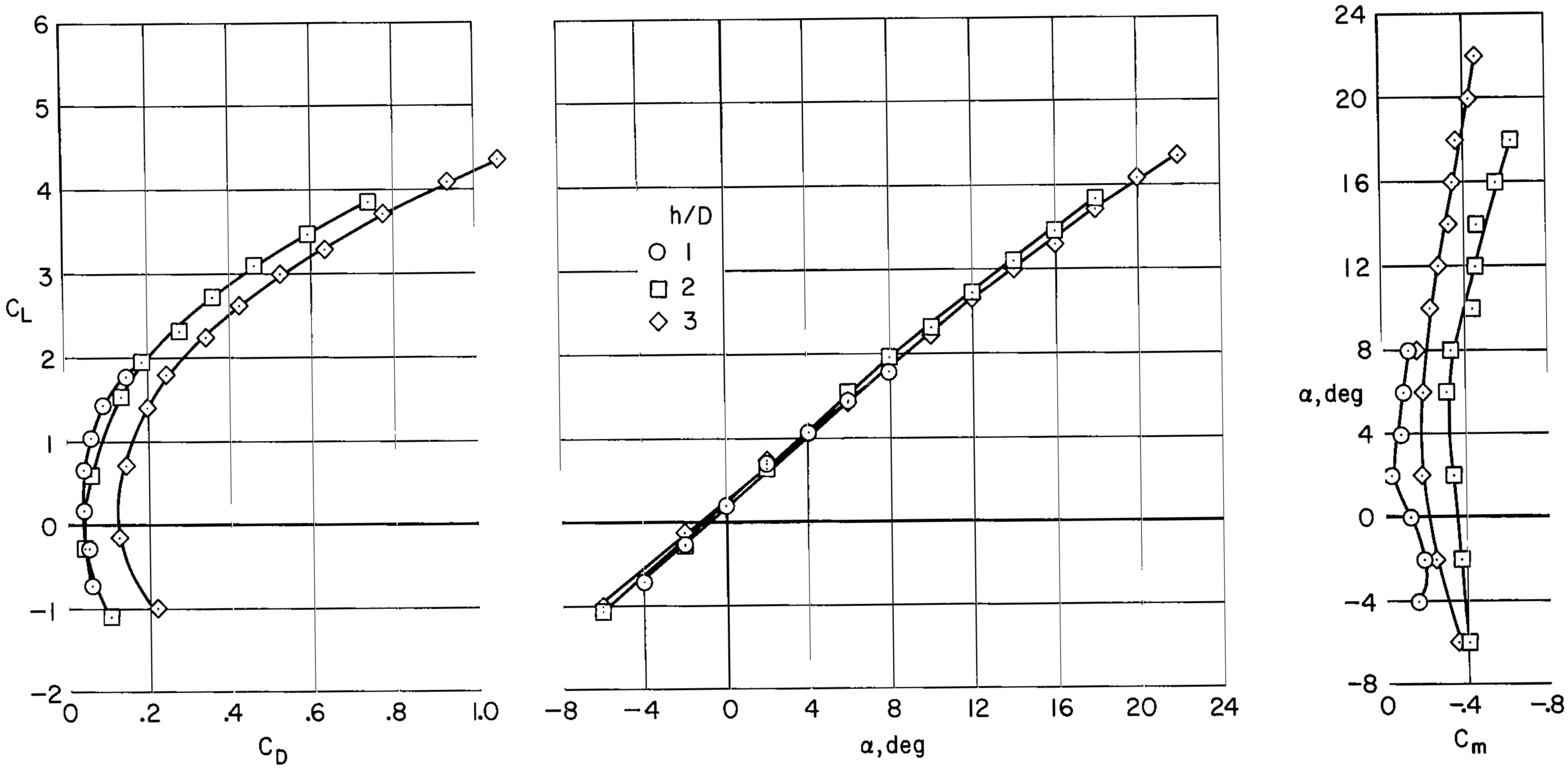
(c) $\delta_D = 50^{\circ}$, V = 48 knots, J = 0.41

Figure 6.- Continued.



(d) $\delta_D = 30^{\circ}$, V = 76 knots, J = 0.65

Figure 6.- Continued.



(e) $\delta_{D_f}/\delta_{D_a} = 5^{\circ}/0^{\circ}$ (cruise configuration), V = 110 knots, J = 0.93

Figure 6.- Concluded.

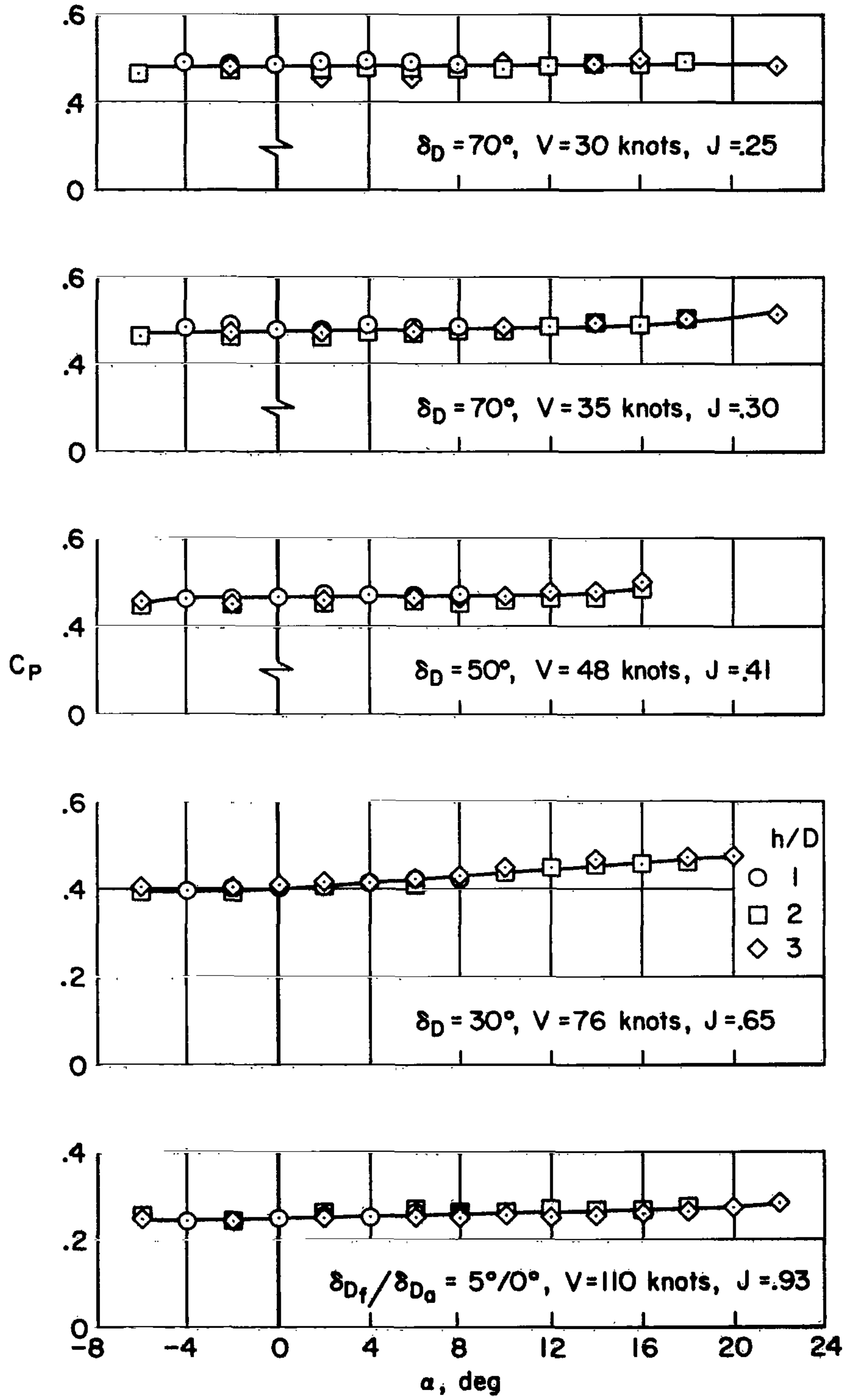
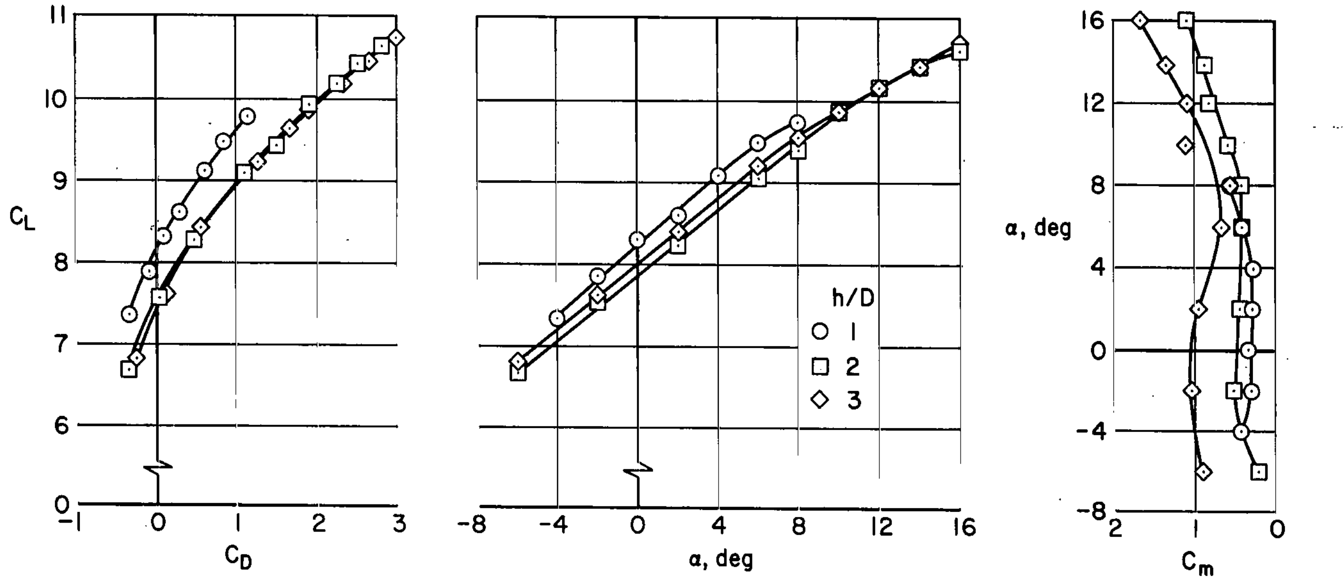
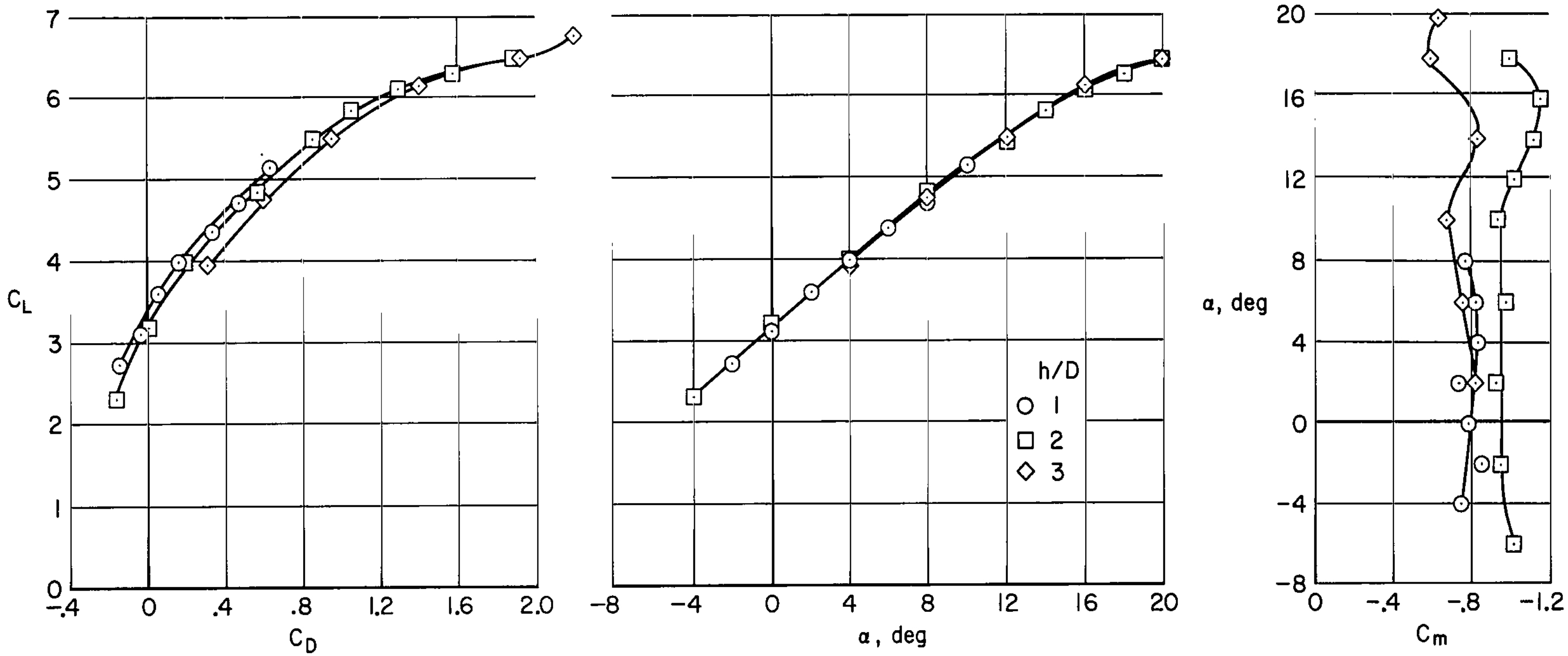


Figure 7.- Variation of power coefficient with angle of attack at three ground heights for several duct configurations; $\delta_{e_f}/\delta_{e_a} = 0^{\circ}/0^{\circ}$.



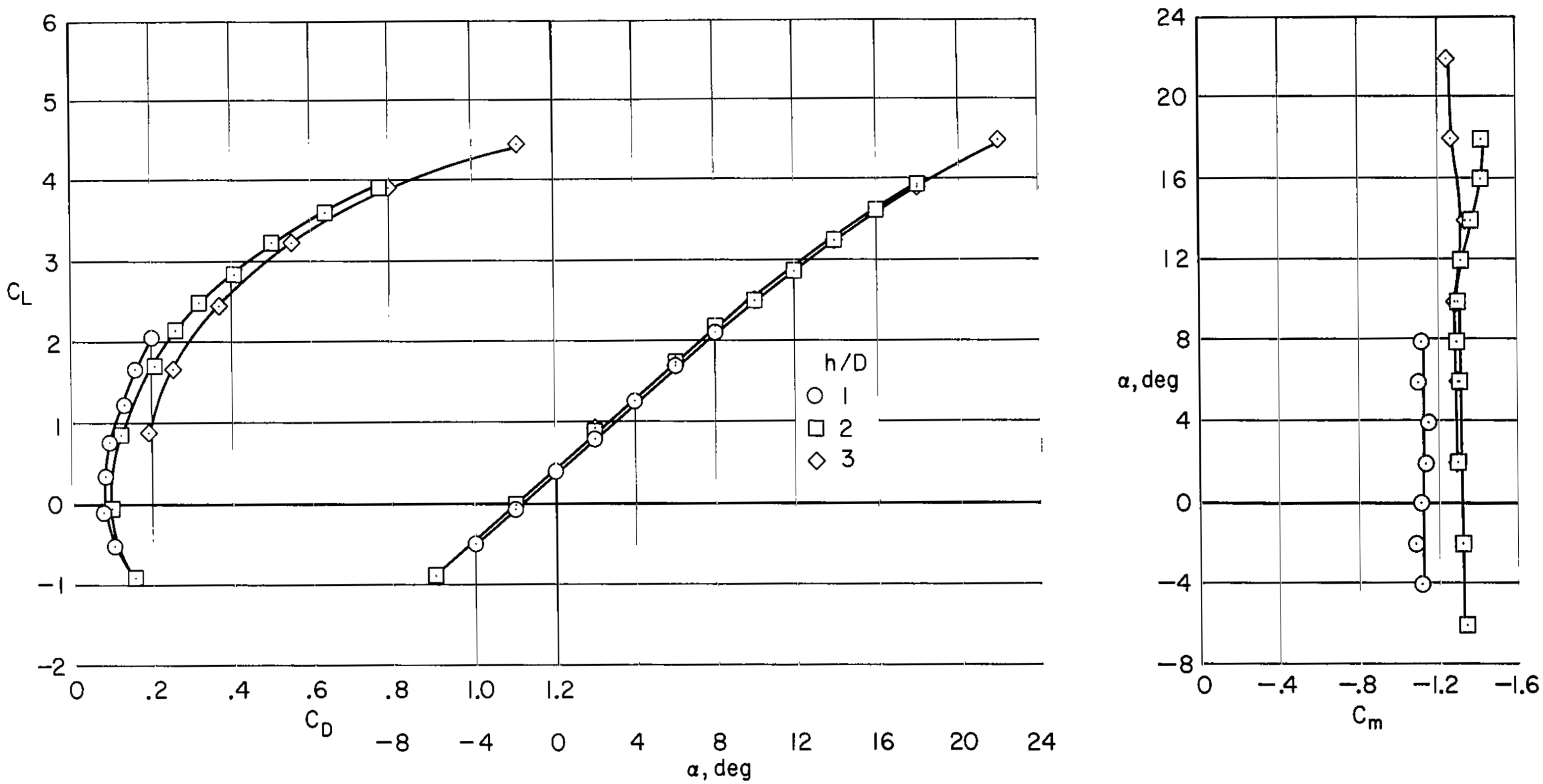
(a) $\delta_D = 50^\circ$, V = 48 knots, J = 0.41

Figure 8.- Longitudinal aerodynamic characteristics of the model at three ground heights with duct exit vanes deflected; $\delta_{e_f}/\delta_{e_a} = -20^\circ/20^\circ$.



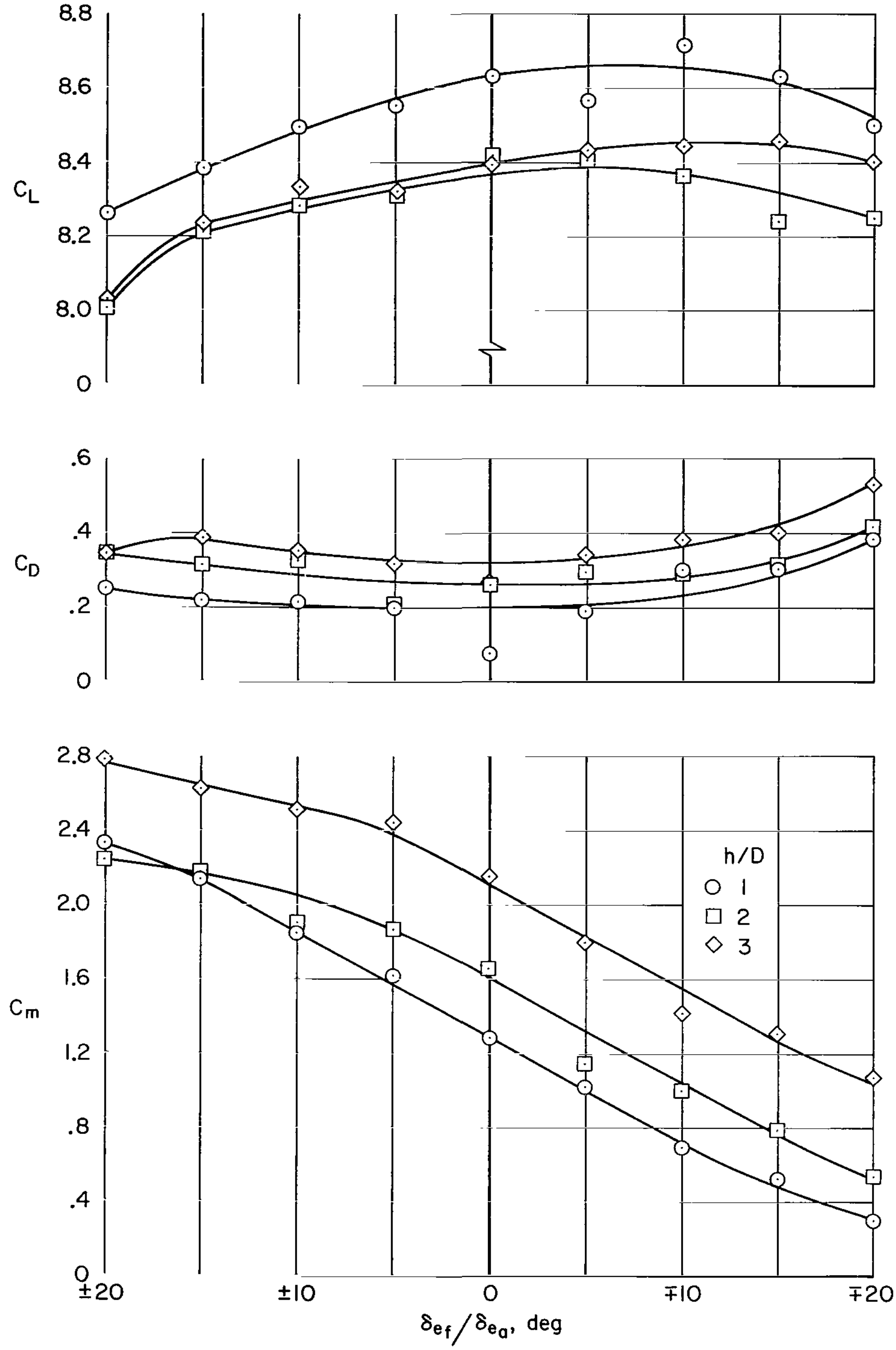
(b) $\delta_D = 30^\circ$, V = 76 knots, J = 0.65

Figure 8.- Continued.



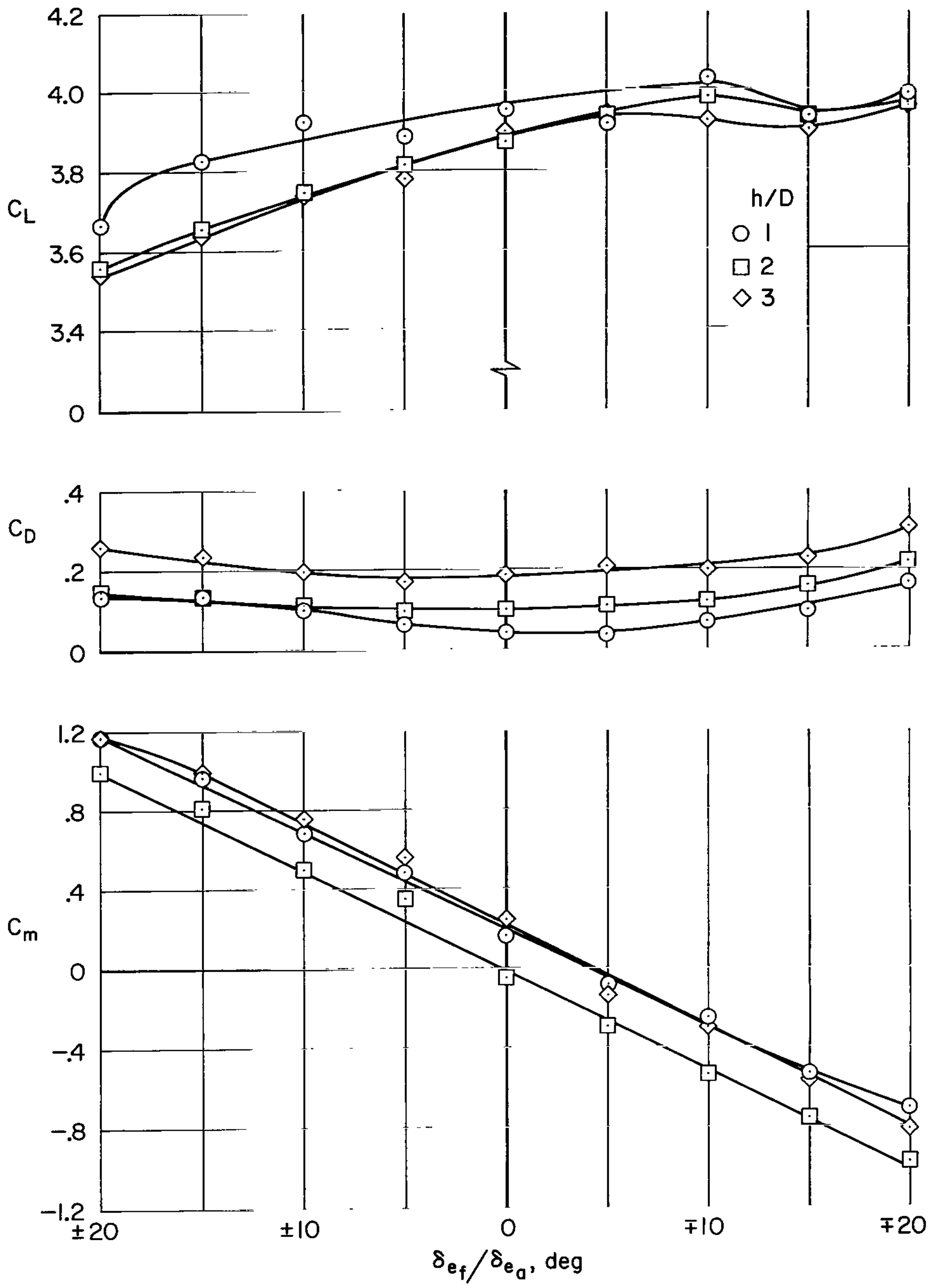
(c) $\delta_{D_f}/\delta_{D_a} = 5^\circ/0^\circ$ (cruise configuration), V = 111 knots, J = 0.95

Figure 8.- Concluded.



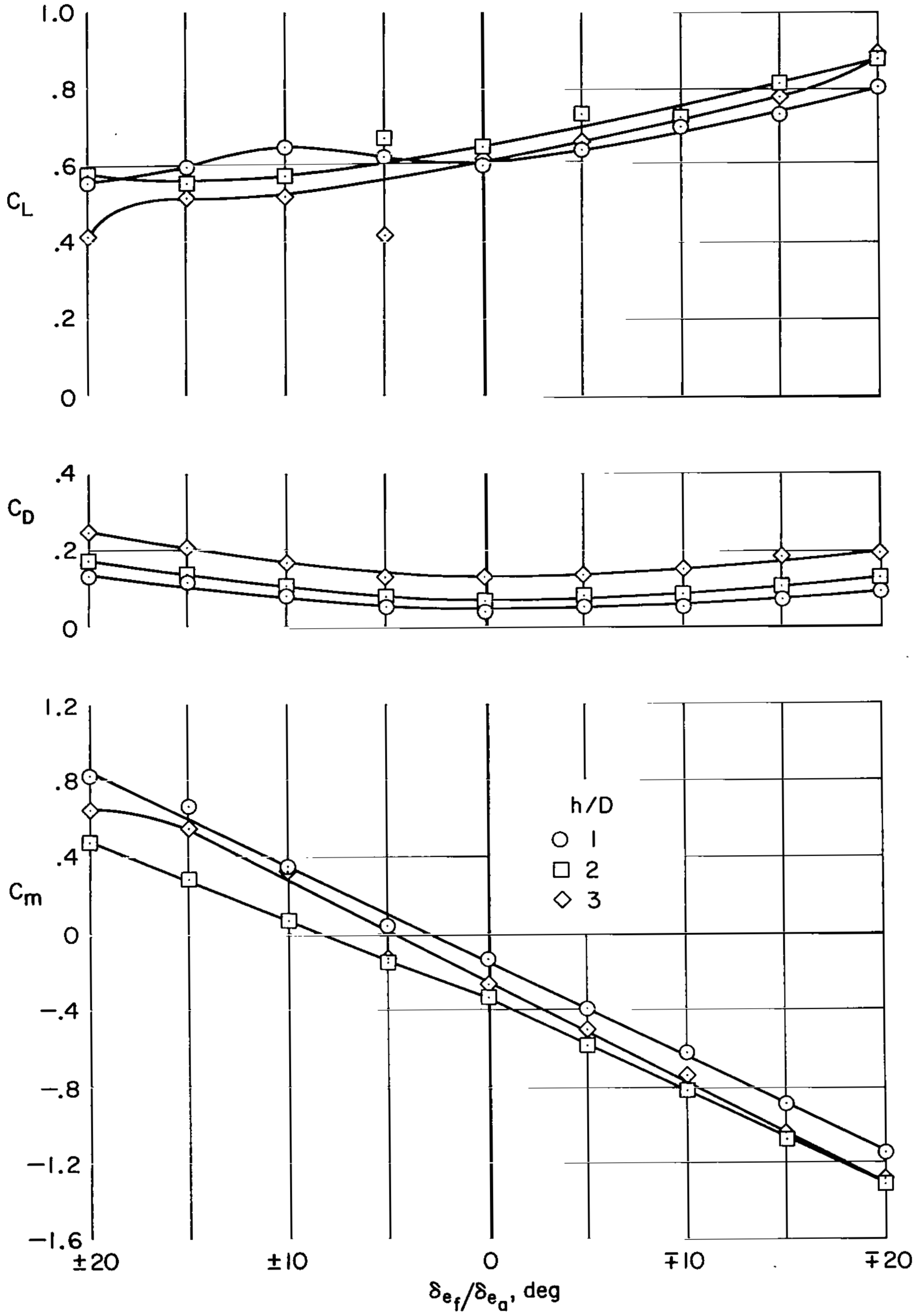
(a) $\delta_D = 50^\circ$, V = 48 knots, J = 0.41

Figure 9.- Longitudinal pitch control effectiveness of differential fore-aft duct exit vane deflection; $\alpha = 0^\circ$.



(b) $\delta_D = 30^\circ$, V = 76 knots, J = 0.65

Figure 9.- Continued.



(c) $\delta_{D_f}/\delta_{D_a} = 5^\circ/0^\circ$ (cruise configuration), V = 111 knots, J = 0.95

Figure 9.- Concluded.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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